

# Recent results on $\phi_3$ at Belle

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**Abstract.** We report results of measurement of the unitarity triangle angle  $\phi_3$  with  $B^+ \rightarrow D^{(*)}K^+$  Dalitz plot analysis and related issues with  $B^0 \rightarrow D_s^{*+}\pi^-$  and  $B^0 \rightarrow D_s^{*-}K^+$  decay processes. The Dalitz analysis improves accuracy of the angle  $\phi_3$  as  $78.4^\circ \substack{+10.8^\circ \\ -11.6^\circ} \pm 3.6^\circ \pm 8.9^\circ$  and the branching fractions are found to be  $B^0 \rightarrow D_s^{*+}\pi^- (K^-)$  decays are set as  $\mathcal{B}(B^0 \rightarrow D_s^{*+}\pi^-) = (1.75 \pm 0.34(\text{stat}) \pm 0.17(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow D_s^{*-}K^+) = (2.02 \pm 0.33(\text{stat}) \pm 0.18(\text{syst}) \pm 0.13(\mathcal{B})) \times 10^{-5}$ .

## 1. Introduction

Determinations of the Kobayashi-Maskawa matrix elements [1] provide important checks on the consistency of the standard model and ways to search for new physics. In decades, several methods have been discussed to provide interior angles  $\phi_1$ ,  $\phi_2$  and  $\phi_3$  of the unitarity triangle. The  $\phi_3$  measurement is still on the way since the measurement has been statistically limited even with modern electron-positron B factories. Two of those analyses to evaluate  $\phi_3$  are reported here. As space is limited, Belle experiment and KEKB accelerator are not explained here. Detailed description of the Belle detector is found elsewhere [2].

## 2. Measurement of the branching fractions for $B^0 \rightarrow D_s^{*+}\pi^-$ and $B^0 \rightarrow D_s^{*-}K^+$

The time-dependent  $CP$  analysis of the  $B^0(\bar{B}^0) \rightarrow D^{*\mp}\pi^\pm$  system provides a theoretically clean measurement of the product  $R_{D^*\pi} \sin(2\phi_1 + \phi_3)$  [3], where  $R_{D^*\pi}$  is the ratio of the magnitudes of the doubly Cabibbo-suppressed decay amplitude to the Cabibbo-favoured decay amplitude. Unlike the  $B^0 \rightarrow D^{*\mp}\pi^\pm$  process,  $B^0 \rightarrow D_s^{*+}\pi^-$ , which is predominantly a spectator process with a  $b \rightarrow u$  transition, does not have contributions from  $\bar{B}^0$  decays to the same final state and can provide clean experimental access to  $R_{D^*\pi}$ . Assuming SU(3) flavour symmetry between  $D^*$  and  $D_s^*$ ,  $R_{D^*\pi}$  is given by

$$R_{D^*\pi} = \tan \theta_C \left( \frac{f_{D^*}}{f_{D_s^*}} \right) \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^{*+}\pi^-)}{\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+)}}, \quad (1)$$

where  $\theta_C$  is the Cabibbo angle,  $f_{D^*}$  and  $f_{D_s^*}$  are the meson form factors, and the  $\mathcal{B}$ 's stand for the corresponding branching fractions. The  $B^0 \rightarrow D_s^{*+}\pi^-$  process, in addition, does not have a penguin loop contribution and hence can in principle be used to determine  $|V_{ub}|$  [4].

The decay  $B^0 \rightarrow D_s^{*+}\pi^-$  does not have a contribution from the  $W$ -exchange amplitude, as the quark-antiquark pair with the same flavor, required for such a diagram, is absent from the final state. We assume the  $W$ -exchange contributions in  $B^0 \rightarrow D^{*\mp}\pi^\pm$  to be negligible, in making the correspondence between  $D^{*+}\pi^-$  and  $D_s^{*+}\pi^-$  in the  $R_{D^*\pi}$  calculation. The size of

**Table 1.** Efficiency ( $\epsilon$ ), yield( $N_{\text{sig}}$ ), branching fraction ( $\mathcal{B}$ ), and statistical significance not including systematic uncertainties ( $\mathcal{S}$ ) from the fits to the data obtained individually in the three  $D_s^+$  modes as well as from the simultaneous fit. The second uncertainty on the  $\mathcal{B}$ 's is due to the uncertainties in  $D_s^+$  decay branching fractions.

$B^0$ mode	$D_s^+$ mode	$\epsilon(\%)$	$N_{\text{sig}}$	$\mathcal{B}(10^{-5})$	$\mathcal{S}(\sigma)$
$B^0 \rightarrow D_s^{*+}\pi^-$	$\phi(K^+K^-)\pi^+$	15.2	$32 \pm 8$	$1.58 \pm 0.40 \pm 0.24$	3.2
	$\bar{K}^+(892)^0(K^-\pi^+)K^+$	7.9	$29 \pm 10$	$2.30 \pm 0.60 \pm 0.35$	2.6
	$K_S^0 K^+$	8.0	$13 \pm 7$	$1.78 \pm 0.92 \pm 0.11$	2.2
	Simultaneous	...	...	$1.75 \pm 0.34 \pm 0.11$	6.6
$B^0 \rightarrow D_s^{*-}K^+$	$\phi(K^+K^-)\pi^+$	13.4	$33 \pm 8$	$1.81 \pm 0.41 \pm 0.27$	3.2
	$\bar{K}^+(892)^0(K^-\pi^+)K^+$	6.4	$23 \pm 7$	$2.22 \pm 0.66 \pm 0.34$	2.8
	$K_S^0 K^+$	6.9	$14 \pm 5$	$2.14 \pm 0.80 \pm 0.13$	3.1
	Simultaneous	...	...	$2.02 \pm 0.33 \pm 0.13$	8.6

the W-exchange diagram can be estimated from the  $B^0 \rightarrow D_s^{*-}K^+$  decay, which proceeds only via  $W$  exchange. The  $B^0 \rightarrow D_s^{*-}K^+$  branching fraction was expected to be enhanced due to rescattering effects [5, 6]. Here we briefly report an improved measurement of the branching fractions for  $B^0 \rightarrow D_s^{*+}\pi^-$  and  $B^0 \rightarrow D_s^{*-}K^+$  with a data sample consisting of  $657 \times 10^6$   $B\bar{B}$  pairs. Detailed description of the analysis is found elsewhere [7].

The signal is reconstructed in three  $D_s^+$  modes:  $\phi\pi^+$  with  $\phi \rightarrow K^+K^-$ ,  $\bar{K}^*(892)^0 K^+$  with  $\bar{K}^*(892)^0 \rightarrow K^-\pi^+$ , and  $K_S^0 K^+$  with  $K_S^0 \rightarrow \pi^+\pi^-$ . After applying Belle standard event selection criteria, we obtained results of fits (Figure 1) summarized in Table 1. The significance is defined as  $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$ , where  $\mathcal{L}_{\text{max}}(\mathcal{L}_0)$  are the likelihoods for the best fit and with the signal branching fraction fixed to zero. Table 2 summarizes the systematic uncertainties involved. The overall systematic uncertainty is obtained by adding these contributions in quadrature.

We obtain  $\mathcal{B}(B^0 \rightarrow D_s^{*+}\pi^-) = (1.75 \pm 0.34(\text{stat}) \pm 0.17(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow D_s^{*-}K^+) = (2.02 \pm 0.33(\text{stat}) \pm 0.18(\text{syst}) \pm 0.13(\mathcal{B})) \times 10^{-5}$  with significance of  $6.1\sigma$  and  $8.0\sigma$ , respectively, where the systematic uncertainties on the signal yield as well as the statistical uncertainties are included in the significance evaluation. Using observed value for the  $B^0 \rightarrow D_s^{*+}\pi^-$  branching fraction, the latest values for  $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+) = (2.76 \pm 0.13) \times 10^{-3}$ ,  $\tan\theta_C = 0.2314 \pm 0.0021$  [8], and the theoretical estimate of the ratio  $f_{D_s^+}/f_{D^+} = (1.164 \pm 0.006(\text{stat}) \pm 0.020(\text{syst}))$  [9], we obtain

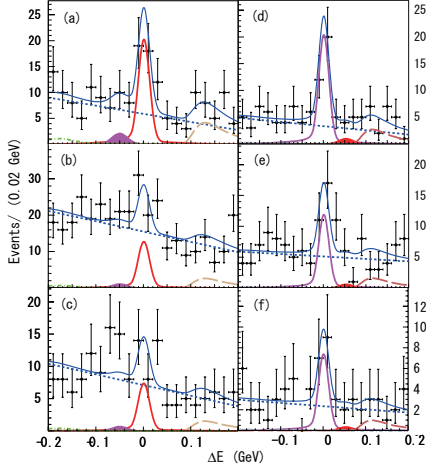
$$R_{D^*\pi} = (1.58 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}) \pm 0.03(\text{th}))\%, \quad (2)$$

where the first error is statistical, the second corresponds to the experimental systematic uncertainty, and the third accounts for the theoretical uncertainty in the  $f_{D_s^+}/f_{D^+}$  estimation. We have assumed that the ratio  $f_{D_s}/f_D$  is equal to the ratio of vector meson decay constants,  $f_{D_s^*}/f_{D^*}$ . The value we obtain for  $R_{D^*\pi}$  is consistent with theoretical expectation of 2%.

The observed value for the  $B^0 \rightarrow D_s^{*-}K^+$  branching fraction is 2 orders of magnitude lower than that for the Cabibbo-favoured decay  $B^0 \rightarrow D^{*-}\pi^+$ .

### 3. $\phi_3$ measurement with a Dalitz plot analysis of $B^+ \rightarrow D^{(*)}K^+$ decay

Among various methods to measure the angle  $\phi_3$  using  $CP$  violation in  $B \rightarrow DK$  decays [10-14], three body final states such as  $K_S^0\pi^+\pi^-$  have been suggested as promising modes for the extraction of  $\phi_3$  [15]. Assuming no  $CP$  asymmetry in neutral  $D$  decays, the amplitude of the



**Figure 1.** The simultaneous fit in the  $B^0 \rightarrow D_s^{*+} \pi^-$  [(a)  $\phi \pi$ , (b)  $K^{*0} K$ , and (c)  $K_S^0 K$  modes] and the  $B^0 \rightarrow D_s^{*-} K^+$  [(d) - (f)] signal modes. Signal peaks are shown by the solid curves, while the solid-filled curves represent the cross-feed.

**Table 2.** Contributions to the systematic uncertainty.

Source	Contribution (%)	
	$D_s^{*+} \pi^-$	$D_s^{*+} K^-$
$D_s^+$ branching fraction uncertainties		
Signal	5.9	6.2
Peaking background	1.5	1.9
Total( $\mathcal{B}$ )	6.1	6.5
Tracking efficiency	4.0	4.0
Photon detection efficiency	7.0	7.0
Particle identification efficiency	2.4	2.1
$K_S^0$ efficiency	1.1	1.1
$\mathcal{LR}$	0.6	0.5
$N_{B\bar{B}}$	1.4	1.4
MC statistics	1.4	1.6
PDF shape	3.4	1.5
Fit bias	0.9	0.3
Total (other)	9.4	8.8

**Table 3.**  $CP$  fit results. The first error is statistical, the second is experimental systematic, and the third is the model uncertainty. The error in combined result of  $\phi_3$  is only statistical. Consult the reference for detailed results [16].

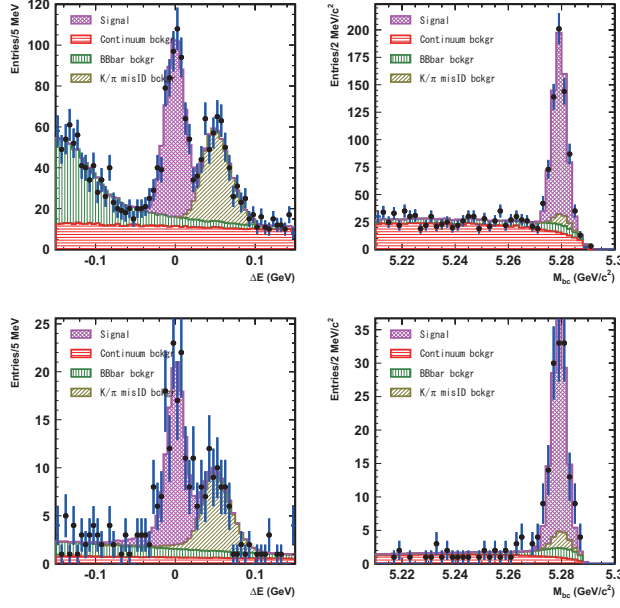
Parameter	$1\sigma$ interval	$2\sigma$ interval	Systematic error	Model uncertainty
$\phi_3$	$(78.4_{-11.6}^{+10.8})^\circ$	$54.2^\circ < \phi_3 < 100.5^\circ$	$3.6^\circ$	$8.9^\circ$
$r_{DK}$	$0.160_{-0.038}^{+0.040}$	$0.084 < r_{DK} < 0.239$	0.011	$+0.050$ $-0.010$
$r_{D^*K}$	$0.196_{-0.069}^{+0.072}$	$0.061 < r_{D^*K} < 0.271$	0.012	$+0.062$ $-0.012$
$\delta_{DK}$	$(136.7_{-15.8}^{+13.0})^\circ$	$102.2^\circ < \delta_{DK} < 162.3^\circ$	$4.0^\circ$	$22.9^\circ$
$\delta_{D^*K}$	$(341.9_{-19.6}^{+18.0})^\circ$	$296.5^\circ < \delta_{D^*K} < 382.7^\circ$	$3.0^\circ$	$22.9^\circ$

neutral  $D$  decays from  $B^\pm \rightarrow DK^\pm$  as a function of Dalitz plot variables  $m_+^2 = m_{K_S^0 \pi^+}^2$  and  $m_-^2 = m_{K_S^0 \pi^-}^2$  is

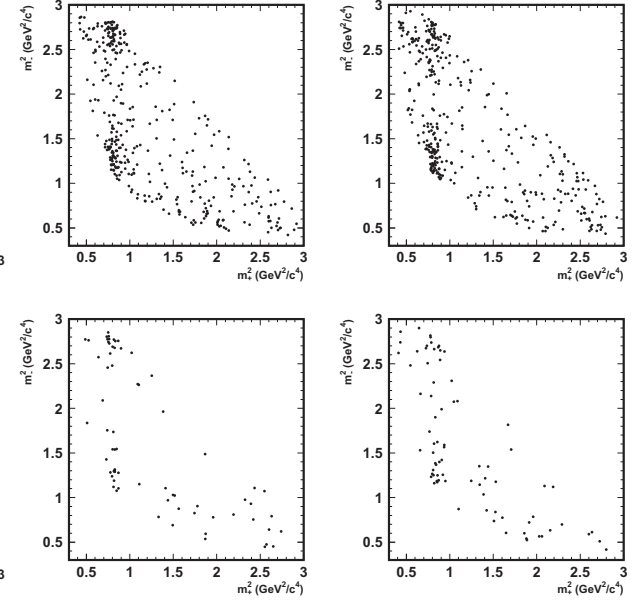
$$M_\pm = f(m_\pm^2, m_\mp^2) + r e^{\pm i\phi_3 + i\delta} f(m_\mp^2, m_\pm^2), \quad (3)$$

where  $f(m_+^2, m_-^2)$  is the amplitude of the  $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$  decay,  $r$  is the ratio of the magnitudes of the two interfering amplitudes, and  $\delta$  is the strong phase difference between them. The  $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$  decay amplitude  $f$  can be determined from a large sample of flavor-tagged  $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$  decays produced in  $e^+ e^- \rightarrow q \bar{q}$  continuum process. Once  $f$  is known, a simultaneous fit of  $B^+$  and  $B^-$  data allows the contribution of  $r$ ,  $\phi_3$  and  $\delta$  to be separated.

In this paper, we report a preliminary result of a measurement of  $\phi_3$  using the modes  $B^+ \rightarrow DK^+$  and  $B^+ \rightarrow D^* K^+$  with  $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ , based on a  $605 \text{ fb}^{-1}$  data sample. Detailed description is found in reference [16]. After event selection (Figure 2 and 3), we obtained  $\phi_3$  and other parameters by fitting the Dalitz plots for two event samples,  $B^+ \rightarrow DK^+$ ,  $B^+ \rightarrow D^* K^+$  and combined results of angle  $\phi_3$  as  $78.4^\circ_{-11.6}^{+10.8} \pm 3.6^\circ \pm 8.9^\circ$  (Table 3).



**Figure 2.**  $\Delta E$  and  $M_{bc}$  distributions for the  $B^+ \rightarrow DK^+$  (top) and  $B^+ \rightarrow D^*K^+$  (bottom) event samples. Points with error bars are the data and the histogram is the result of a MC simulation according to the fit result.



**Figure 3.** Dalitz distributions of  $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$  decays from selected  $B^+ \rightarrow DK^+$  (top) and  $B^+ \rightarrow D^*K^+$  (bottom) candidates, shown separately for  $B^-$  (left) and  $B^+$  (right) tags.

## 4. Conclusion

We report results of measurements of the angle  $\phi_3$  of Kobayashi-Maskawa triangle with  $B^+ \rightarrow D^{(*)}K^+$  Dalitz plot analysis and related issues with  $B^0 \rightarrow D_s^{*+}\pi^-$  and  $B^0 \rightarrow D_s^{*-}K^+$  decay processes. Measurement of angle  $\phi_3$  is on the way to verify the Standard Model prediction, and will be a rich physics subject for a decade with next generation  $B$  factories and LHC.

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